# A Dual Multilayer Insulation Blanket Concept to Radically Reduce Heat Loss From Thermally Controlled Spacecraft and Instruments

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**At large distances from the Sun (e.g. Jupiter/Saturn), the solar flux is less than 4% that at Earth. This requires very large solar arrays to meet the power demands of a typical new mission concept. Heat loss through Multi-Layer Insulation (MLI) blankets typically constitutes the vast majority of the total heat loss. Hence, improvements to MLI blankets that reduce heat loss are advantageous to the spacecraft design. The overall effective emittance (ε*) of MLI is usually a range dependent on the number of layers, size of blanket, seams, feedthroughs, layer density and operating temperatures of the heat source and heat sink. A concept has been developed at JPL to reduce the ε* by as much as a factor of two, which produces a corresponding reduction in heat losses. This concept utilizes two MLI blankets physically separated by traditional bumpers or spacers used for micrometeoroid protection. The outer surface of the inner blanket and the inner surface of the outer blanket are low emissivity surfaces to further minimize the total ε* of the overall dual MLI system. Analytical predictions of a dual MLI concept have been made using test data based ε* correlations. A development test has been conducted to validate the dual blanket design's performance. This paper will describe the dual blanket design concept, schemes for its implementation, and the corresponding test results to validate its performance.**

## Nomenclature

| | | |
|---|---|---|
| $\varepsilon^*$ | = | MLI blanket effective emittance |
| $\sigma$ | = | Stefan-Boltzmann constant |
| *AM* | = | aluminized mylar |
| *CK* | = | carbon filled black kapton |
| *DAM* | = | dacron netting and aluminized mylar |
| *EAK* | = | embossed aluminized kapton |
| *JPL* | = | Jet Propulsion Laboratory |
| *MLI* | = | Multilayer Insulation |
| $N$ | = | MLI layer density |
| $N_S$ | = | number of MLI layers |
| $T_c$ | = | cold sink temperature |
| $T_h$ | = | hot sink temperature |
| $T_{avg}$ | = | average MLI blanket temperature |

## I. Introduction

THE primary motivation for this research is to develop MLI blanket concepts that could dramatically reduce the heat loss through these blankets. Another important consideration is to ensure that they are applicable to and implementable on typical spacecraft with complicated shapes, feedthroughs and penetrations. These concepts should

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also be robust for launch vibrations and loading. Several concepts that have been documented before in literature(Refs 1-4) do provide significant improvements in MLI performance but they tend to be applicable to very simple shapes (simple rectangular, cylindrical in nature), are not very robust for launch loading, and are quite difficult to implement on complex shaped spacecraft. Hence, this research was focused on expanding current MLI concepts that have been proven for implementation and are robust for launch and applicable to complicated shapes. Furthermore, these concepts have the same areal mass density as traditional MLI to ensure that they do not increase the blanket mass significantly.

For any MLI blanket, there are several key parameters that affect its effective emittance (ε*): number of layers, layer density (how tightly/closely the layers are packed), seams (stitched edges) and MLI source/sink temperatures. In general increasing the number of layers decreases the ε*, however beyond 20 layers or so, the relative improvement yields marginal returns at the expense of increased mass, which is usually not desirable. Figure 1 shows the diminishing returns that would be realized by increasing the number of layers beyond ~20 because the ε* vs. number of layers plot flattens out in an asymptotic fashion.

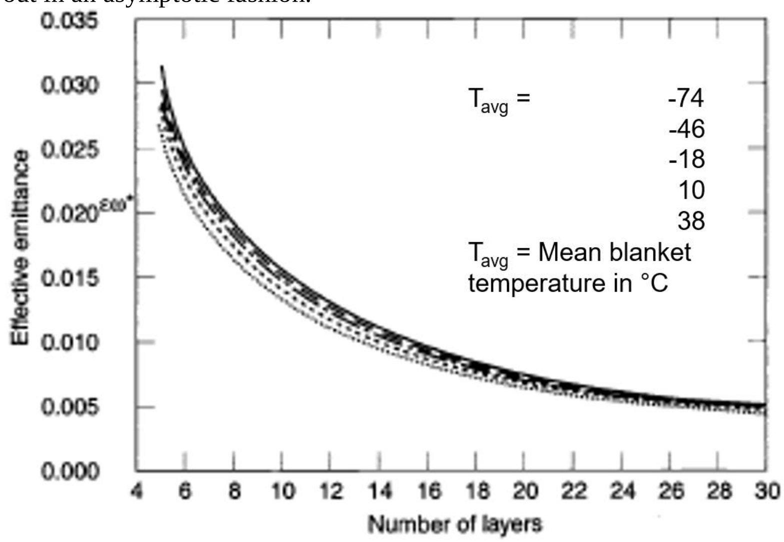


**Figure 1. ε* vs. Number of MLI layers (Ref 5)**

The layer density is extremely important because the more tightly packed the layers are, the more the layers touch each other and contact conduction between them starts to dominate the radiative isolation between adjacent shields. Keeping the MLI layers loose is most desirable but it is hard to achieve in real practice, particularly around corners when the layers inevitably get crushed (unless each layer is increasing slightly in area, but this requires significant labor to achieve this). Stitched seams are the ultimate form of increasing layer density because they are crushed during the stitching process, so this is the biggest culprit in increasing ε*. The source and sink temperatures both tend to make the ε* higher as the temperatures are lowered. The reason for this is that the lower the temperature is, the lower the relative magnitude of the radiation coupling compared to the interlayer contact conduction. This leads to less of a radiation shield dominant MLI (ideal isolation) and more of a conductive isolation, which is inherently inferior.

The Lockheed equation (Ref 6) is an empirical correlation derived from test data of various blanket designs at the Lockheed Corporation (now Lockheed Martin). The equation accounts for the effects of layer density, the number of layers, seams, and temperature. The equation includes terms for conductive and radiative heat transfer through a blanket. The Lockheed equation is:

$$\epsilon^* = \frac{7.30*10^{-8}N^{2.63}}{\sigma(N_s+1)}\left(\frac{1}{T_h^2+T_c^2}\right) + \frac{7.07*10^{-10}(0.043)(2)}{\sigma N_s}\left(\frac{T_h^{4.67}-T_c^{4.67}}{T_h^4-T_c^4}\right) \quad (1)$$

where N is the layer density (layers/cm), $N_s$ is the number of layers, $T_h$ is the hot sink temperature (K), $T_c$ is the cold sink temperature (K), and σ is the Stefan-Boltzmann constant ($W/m^2K^4$). For a single blanket configuration, the blanket ε* can be calculated by simply using the equation.

For a given set of source and sink temperatures, and with limitations of numbers of layers (to minimize mass), the dominant parameter is the layer density and the relative spacing of seams. Larger blankets have a smaller areal fraction of seams. Hence, they tend to be lower in ε*. When the seams or layer density cannot be reduced, the only reasonable way to reduce the ε* is to create separate blankets (nominally two blankets with same total number of layers as a single individual blanket to maintain the same mass). Then if the two separated blankets have low emissivity external layers facing each other (outer surface of first blanket and inner surface of second one), and since these layers have very low emissivities that are comparable to the ε* of a MLI blanket, the additional thermal isolation between these two facing layers is in series with the ε* of each of the two blankets. This provides significantly lower overall ε* for the two blanket system when compared to that of a single full blanket. The main reason this provides that advantage when compared to the facing layers sewn together (as they would in a single full blanket) is that the conduction coupling between these two facing layers is eliminated. Figure 2 illustrates this concept.

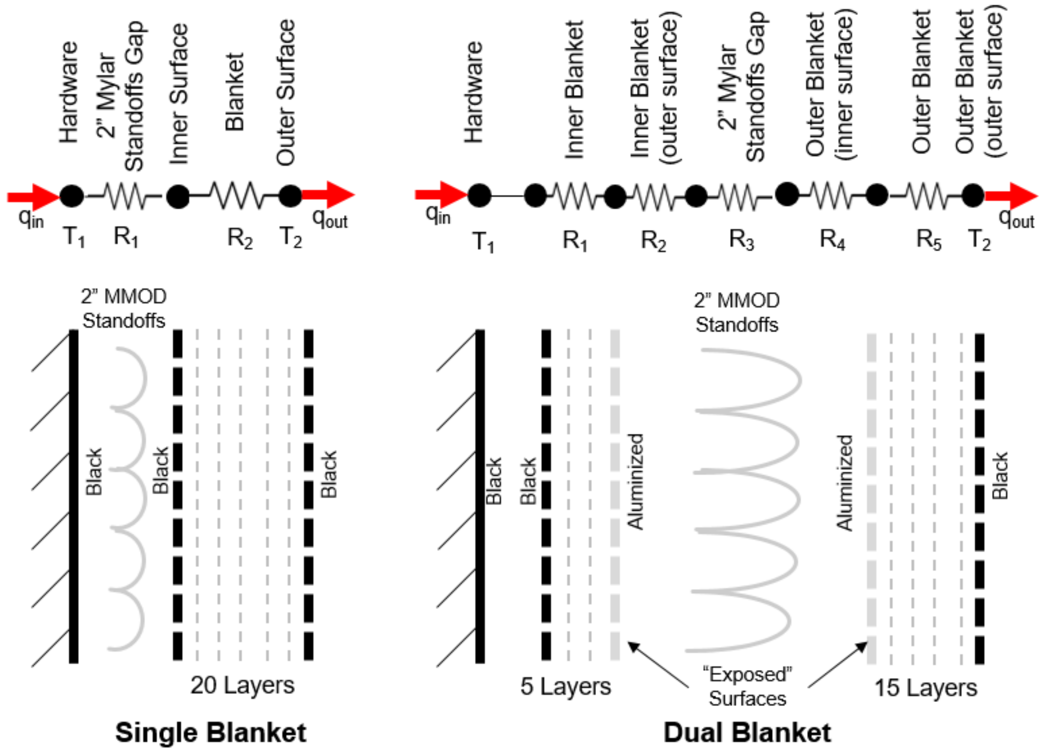


**Figure 2. Single vs Dual Blanket Concept**

Analytical predictions for performance of a dual blanket configuration are more complicated since calculating new ε* values will change the sink temperatures that each blanket sees. To overcome this, a numerical scheme was implemented in Microsoft Excel that iterates the ε* values of both blankets until the calculated temperatures result in an absolute difference error smaller than some tolerance ($10^{-6}$).

Of course, two conditions have to be satisfied to achieve the potential improvement of this concept: the two blankets have to be kept separated by low or negligible thermal conductance standoffs (e.g., very thin standoffs of aluminized Mylar) and they need to have very low emissivities. Aluminized Mylar has an emissivity of approximately 0.04. A highly simplified example of a dual blanket vs. a single blanket is as follows: assume the first blanket has 5 layers and an ε* of 0.05, the second blanket has a ε* of 0.03 for 15 layers, the two inner exposed layers of the two blankets facing each other (and physically separated) have low emissivity surfaces of 0.04. For two equal area planar surfaces facing each other, the following simple radiation heat transfer equation provides the effective emittance, $\varepsilon_{eff}$, of the combination:

$$\frac{1-\varepsilon_1^*}{\varepsilon_1^*} + \frac{1}{\varepsilon_{1,o}} + \frac{1}{\varepsilon_{2,i}} + \frac{1-\varepsilon_2^*}{\varepsilon_2^*} = \frac{1}{\varepsilon_{eff}} \tag{2}$$

Where $\varepsilon_1^*$ and $\varepsilon_2^*$ are the effective emittances of the first and second blankets, respectively; and $\varepsilon_{1,o}$ and $\varepsilon_{2,i}$ are the emissivities of the exposed surfaces of the two blankets facing each other. Then using equation 1, the entire dual blanket system will have an overall $\varepsilon_{eff}$ of $\left[\frac{1-0.05}{0.05}+\frac{1}{0.04}+\frac{1}{0.04}+\frac{1-0.03}{0.03}\right]^{-1}$ or 0.01. For the single blanket with 20 layers the ε* would be $\left[\frac{1-0.05}{0.05}+\frac{1-0.03}{0.03}\right]^{-1}$ or 0.02. This simple example illustrates how to reduce overall ε* by half compared to single blankets by separating the two sub-blankets with low emissivity facing inner layers. Calculations that are more detailed and the results of the testing will be provided later in this paper. In this example, values of ε* computed were a result of two competing effects: Smaller number of layers (5 for first blanket vs. 15 for second) would lead to a higher ε* for the first blanket, whereas a warmer first blanket would lead to it having a lower ε* than the second one. Overall, in this particular example, the first effect dominates and leads to a higher ε* (0.05) for the first blanket when compared to the second one (0.03).

If needed, additional strategies could be implemented to reduce the risk of contaminating the internal surfaces during I&T activities, that could lead to higher overall ε* of MLI.

- More stringent handling requirements and constraints (especially until after the outer MLI blanket is installed)
- Design venting paths to reduce contamination during out outgassing

To investigate the potential for reducing MLI ε* by using a separated dual blanket scheme, a series of tests were conducted in January & February of 2018. Prior to testing, predictions were made for the expected performance during the test and then compared to those measured.

## II. Application of Dual MLI Concept for Future JPL Missions

Two flagship missions (Figure 3) are candidates for application of this dual MLI concept. The first is the Europa Clipper mission that is slated to launch as early as 2022. The second is the Europa Lander mission concept that is being studied for launch as early as 2024. The Europa Clipper spacecraft features a large propulsion module with a cylinder that is maintained between 0 and +35 °C. The cylinder is where an MLI concept from this development test could be best implemented. The Europa Lander descent stage is also planning to employ a dual blanket MLI concept around the propulsion tanks to save heater power during cruise. Roughly, half the heat loss of the cruise stage lander vehicle would be from the descent stage tanks. The Europa Lander spacecraft could also greatly benefit from this potential reduction in heat loss. Both of these missions plan to utilize solar arrays for power and, since both are at ~5 astronomical units (AU) (Jupiter), power is very precious due to the low solar flux at those distances.

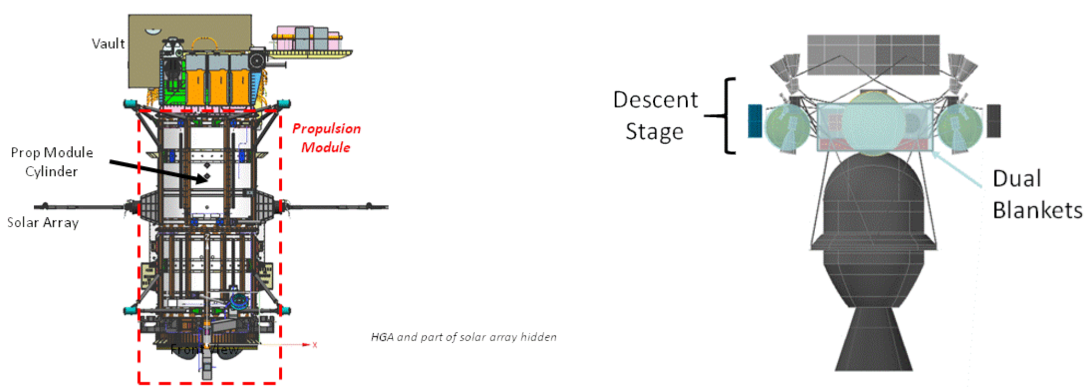


**Figure 3. Europa Clipper (left) & Europa Lander designs (right)**

## III. Test Overview

A development test was designed to characterize the performance of various MLI blanket constructions and configurations. JPL typically uses a 15 to 20 layer blanket with lacing cord-stitched seams at the blanket edges. While this results in a physically robust blanket, there may be room for improvement with respect to thermal performance. MLI performance is particularly important for deep space solar array powered missions where power conservation drives the design at high AU distances. Therefore, blanket design improvements learned from this test could be beneficial to Europa Clipper, a potential Europa Lander, and other potential future missions.

This test chiefly investigates the performance of a 5-layer blanket and a 15-layer blanket arrangement with an engineered offset between the blankets. Using a second MLI blanket offset from the first blanket creates an opportunity to reduce heat loss from that possible by a single blanket alone. With two separate blankets, there can be low emissivity surfaces on the exposed outermost layer of the inner blanket and innermost layer of the outer blanket (inner and outer defined with respect to the hardware). The addition of these two low emissivity surfaces theoretically results in roughly twice the resistance to radiation heat transfer and a corresponding decrease in the heat loss. Additionally, the proposed dual blanket scheme is mass neutral because it still has 20 total layers. Since the outermost layer of the sun-viewing blankets for Europa Clipper and Lander may be black to prevent overheating during inner cruise, the optical properties of the outermost layer were not varied in this test. An advantage of using a black outer layer is that this ensures the temperature of the outer layer is similar to that of the shroud in the test chamber.

The proposed implementation for a dual blanket scheme on Europa Clipper is illustrated in Figure 4. The outer blanket would be supported by structural ribs that appear circumferentially around the prop module cylinder. Pairs of 2.5 mm holes cut into the ribs would be used as lacing cord tie down features for supporting the blanket. The inner blanket would be sized for a conformal fit of the cylinder and fill the gaps between the structural ribs. Aluminized Mylar standoffs would be placed in the gap between the blankets to maintain an offset and provide additional structure support to the outer blanket.

Testing was done in a vacuum chamber with pressure less than $10^{-5}$ torr (1.3 mPa) and a shroud controlled by liquid nitrogen ($LN_2$) to roughly -175 °C. Various blanketing schemes were implemented on an aluminum sheet metal cube with nominal dimensions around 1ft x 1ft x 1ft (0.3 m x 0.3 m x 0.3 m). Each face was independently temperature controlled with kapton film heaters. Thermocouples placed on the inner sides of the cube and the chamber shroud allow calculation of the overall effective emissivity (ε*) for each blanket test case.

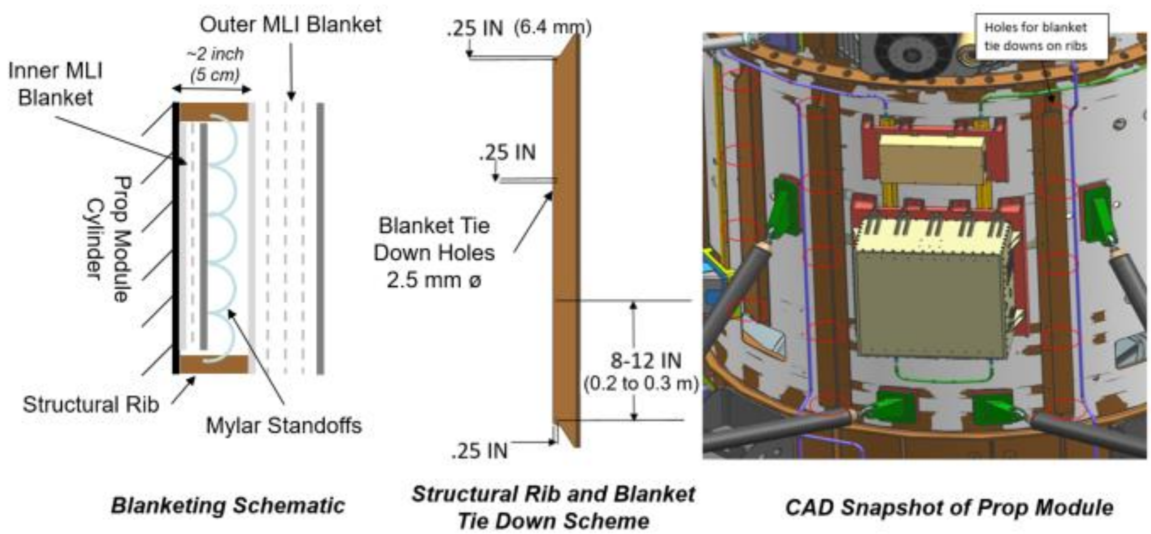


**Figure 4. Proposed implementation of dual blanket scheme on Europa Clipper propulsion module**

## IV. Test Objectives

- Characterize overall effective emissivity, ε*, of several MLI blanket configurations, particularly those involving dual blanket configurations
- Qualitatively determine sensitivity of blanket performance to artifacts of blanket construction that may negatively impact performance such as
    a. Seams
    b. Conductive losses caused by instrumentation, Mylar standoffs, and test setup
    c. Dacron netting
- If a dual blanket configuration demonstrates significant reduction in heat loss over a single blanket configuration, down-select one single blanket and one dual blanket configuration for large scale testing

## V. Test Article

The test article was an aluminum cube with exterior dimensions of approximately 1ft x 1ft x 1ft (0.3 m x 0.3 m x 0.3 m) (Figure 5). Each side of the cube was 1/8in (3 mm) thick. This helped each side to be close to isothermal, which results in a more uniform boundary temperature. Five of the sides were fabricated by a water jet cutter such that they were dovetail when assembled. This improved the isothermal characteristic since fastener interfaces were not needed along some of the cube's edges. The bottom panel contained a 1 in (0.025 m) diameter hole at the center to allow thermocouple and heater cables inside the box to egress. The outside of the cube was covered in black kapton tape. This was done to reduce the temperature difference between the cube and the innermost layer of the first MLI blanket. Therefore, any effect of the dual blanket and aluminized "exposed" surfaces would be magnified during testing.

All thermocouples placed on the test article were 36 AWG and type E. Using a smaller wire gauge reduces parasitic heat loss from the test article. The lead wires for the heaters were 22 AWG. The worst-case total heat loss from all heater and thermocouple wires was predicted to be at most 1.1 W (0.038 W from thermocouples and 1.032 W from heaters), which was between 8 and 42% of the predicted heat loss in test. A kapton film guard heater was installed on the cable bundle on the far end from the cube. However, due to an erroneous boundary condition in the pre-test thermal model, this guard heater was set to the wrong heat input (0.010 W) during testing. Therefore, the parasitic heat loss due to cabling was subtracted from the total heat loss in test to determine the heat loss through MLI only.

To reduce the parasitic heat loss by radiation, the cable bundle was wrapped with aluminum tape for the first foot of cable length outside the cube. A kapton film guard heater was installed on the aluminum wrapped region of the bundle on the far end from the cube. For the first blanket test, thermocouples were placed on the outside of the MLI to determine temperatures on the black outer layer. The left image of Figure 5 shows the inside of the cube with heaters and thermocouples installed. The right image of Figure 5 shows the outside of the cube with black kapton tape surfaces.

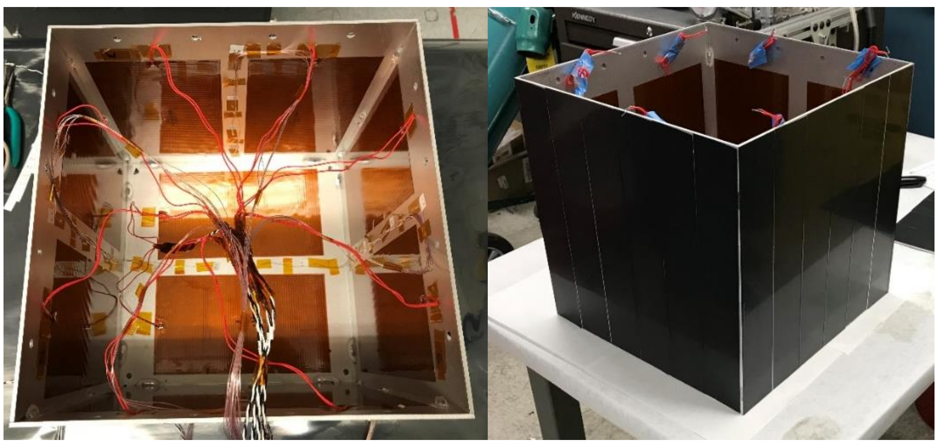

**Figure 5. Test article before the bottom panel was attached**

## VI. Chamber Setup

All testing was conducted at JPL. 26 AWG thermocouples were placed on the shroud in six locations (four on the main shroud and one each at the two circular ends). The test article was supported in the chamber by four sets of 0.020 in (0.5 mm) diameter stainless steel wires (Figure 6). The estimated conductive heat loss from the cube to the chamber for this setup was estimated at 0.1 mW, which was negligible compared to the heat loss of the test article through the MLI. The main chamber shroud and a copper door shroud (Figure 6) controlled the temperatures of the chamber to approximately -175 °C for all test cases. Before each test, there was a check that the outer MLI blanket was not touching the chamber shroud, which would create a conductive heat leak. The wires interface with stainless steel eyebolts at the test article side and stainless steel clips at the chamber side.

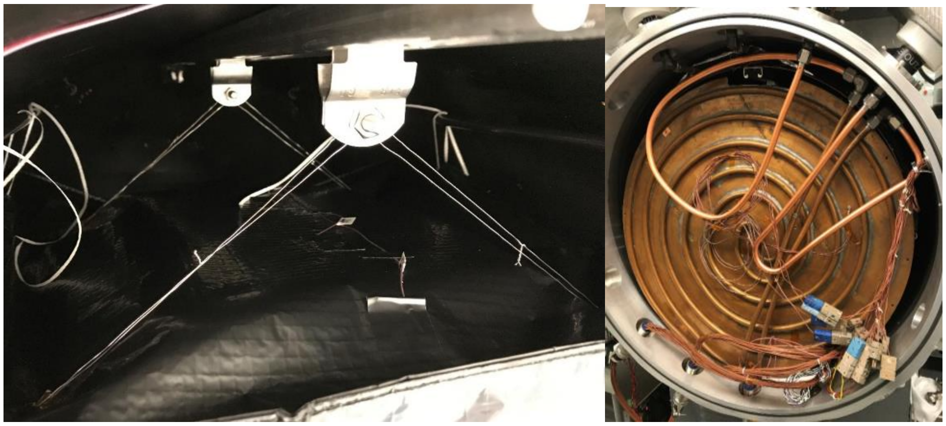

**Figure 6. Stainless steel wires supporting test article (left) & copper door shroud with plumbing installed (right)**

## VII. Test Matrix

The list of all tested blanket constructions and configurations is in Table 1. Each blanket had five sides with sewn seam edges and a sixth side that acted as a flap, which was closed out just before testing. Case 1 is the baseline blanket design for this test. This used a blanket layup with carbon filled black kapton for the inner and outermost layers and 20 single layers each of dacron netting and aluminized Mylar. Therefore, a blanket concept must perform better than case 1 to become a viable candidate for reducing heat loss beyond the baseline design. All blanket cases contain 2 in (0.05 m) aluminized Mylar standoffs between the hardware and the outer blanket. In a single blanket test (cases 1 and 2), the standoffs were placed between the cube and the inside of the blankets. In a dual blanket test, the standoffs were typically placed between the inner and outer blanket. The exception was case 7, which placed the standoffs between the cube and inner blanket, with no engineered gap (via additional standoffs) between the blankets to keep them physically separated, which resulted in the two blankets loosely touching each other. In an actual implementation of a dual MLI configuration in flight hardware, the two blankets would employ short aluminized Mylar standoffs to keep them physically separated. Hence case 7 test results would lead to ε* values that would be higher than what would be achieved in an actual flight application, therefore, the test results for Case 7 would serve as a conservative upper bound for the flight application of this configuration. Additionally, Case 7 is the closest to simulating the flight configuration, albeit lacking the physical standoffs in the test, because for large size blankets, the small standoff would still lead to the two blankets being close to each other in area. Small size blankets, as the one simulated in this test, tend to make the two blankets unequal in area because of the standoff gap, and this had to be accounted in the test correlations explained later in this paper.

Each of the blankets was tested at test article temperatures of roughly +20, +35, and +50 °C. This provided several data points to characterize the change (if any) in blanket performance over a temperature range within limits for many components on the Europa Clipper spacecraft. 0 °C was originally included as a test temperature since it is representative of a lower limit AFT for propulsion hardware. However, cooling the test article from ambient temperature was too time-consuming for this development test because of the large thermal time constants. A future test may improve on this one by testing at lower temperatures to improve knowledge of blanket performance sensitivity to temperature.

| | | Inner Blanket | | | | Outer Blanket | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Case** | **2'' Spacers** | **Inner Surface** | **# Layers** | **Outer Surface** | **2'' Spacers** | **Inner Surface** | **# Layers** | **Outer Surface** | **Seam Modifications** |
| 1 | Yes | | | | | CK | 20, DAM | CK | |
| 2 | Yes | | | | | CK | 20, DAM | CK | Extra seams |
| 3 | | CK | 5, EAK | CK | Yes | CK | 15, DAM | CK | |
| 4 | | CK | 5, EAK | AM | Yes | AM | 15, DAM | CK | |
| 5 | | CK | 5, DAM | AM | Yes | AM | 15, DAM | CK | |
| 6 | | CK | 5, EAK | AM | Yes | AM | 15, DAM | CK | Staggered |
| 7 | Yes | CK | 5, EAK | AM | | AM | 15, DAM | CK | Staggered |
| 8 | | CK | 15, EAK | AM | Yes | AM | 15, DAM | CK | |
| 9 | | CK | 15, EAK | AM | Yes | AM | 15, DAM | CK | Staggered |

**Table 1. Test matrix for MLI blanket testing. CK = carbon filled black kapton; AM = aluminized Mylar; EAK = embossed aluminized kapton; DAM = Dacron netting and aluminum Mylar**

## VIII. Blanket Implementation Process

The exterior surfaces of the blankets were cleaned with isopropyl alcohol before use. All blankets were installed at JPL on a table outside the test chamber. A large, plastic bucket was used for staging the cube during blanket installation (Figure 7). This bucket was cleaned with isopropyl alcohol beforehand to not contaminate either the black kapton tape on the cube or the blanket surfaces.

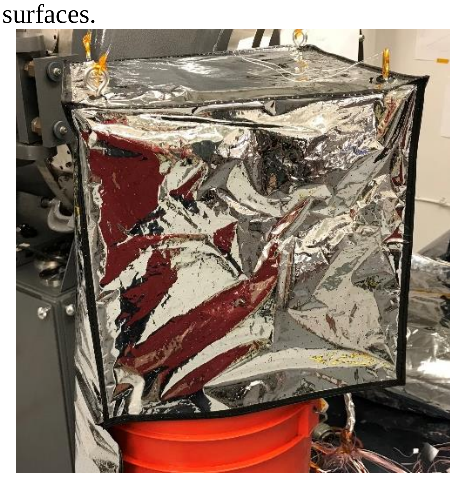

**Figure 7. An inner blanket (5 layer CK, EAK, AM) installed over the cube. The cube was staged on top of a large bucket to facilitate blanket installation before moving the test article into the chamber**

To begin blanket installation, the aluminum cube was placed on top of the bucket with the designated "top face" of the cube facing up. For a single blanket test, the aluminized Mylar standoffs (Figure 8) were installed directly onto the cube surfaces. These standoffs had 3M 966 adhesive on their underside so they can stick to the base surface. Kapton tape was also used to supplement the adhesive. The kapton tape became more necessary in the later test cases as the adhesive performance deteriorated from repetitive use. There was no visible residue left from the adhesive when removing the standoffs. Then the blanket was installed over the cube with standoffs now affixed. For a dual blanket test, the inner blanket was installed first (except test case 7). Then the Mylar standoffs were placed onto the inner blanket. After the standoffs were installed, the outer blanket was placed over the inner blanket (Figure 9). Standoffs were used for all faces except the bottom face since the bottom of the blanket would naturally rest 2 in (0.05

m) below due to gravity. An example of the gap created by the standoffs in a dual blanket configuration is shown in Figure 10.

Starting with the second test case, an improvement was made to the standoff scheme by creating three-standoff “unit cells” along the top edges of the cube (Figure 8). These unit cells prevented gravity driven sag of the blanket edges at the top face.

The edges along the bottom blanket flap were closed out with 1 in (0.025 m) wide kapton tape (Figure 11). Once blanketing was complete, stainless steel clips were attached to the wires that would suspend the cube in the chamber. The clips slid into a stainless steel railing installed at the top of the chamber and the test article is left floating (Figure 12). Adjustments were made with the locations of the clips to ensure the outer blanket did not contact the shroud.

**Figure 8. The left image 2” (0.05 m) tall aluminized Mylar standoffs installed on the outside surfaces of the inner blanket. The right image shows a close-up of one of the three standoff “unit cells” that helped prevent the blanket from sagging at the top corners.**

**Figure 9. An outer blanket (15 layer AM, DAM, CK) being installed over the cube and inner blanket.**

**Figure 10. Interior view of a dual blanket scheme with the Mylar standoffs providing a roughly 2” (0.05 m) gap between blankets (blue lines added for clarity to see spacing).**

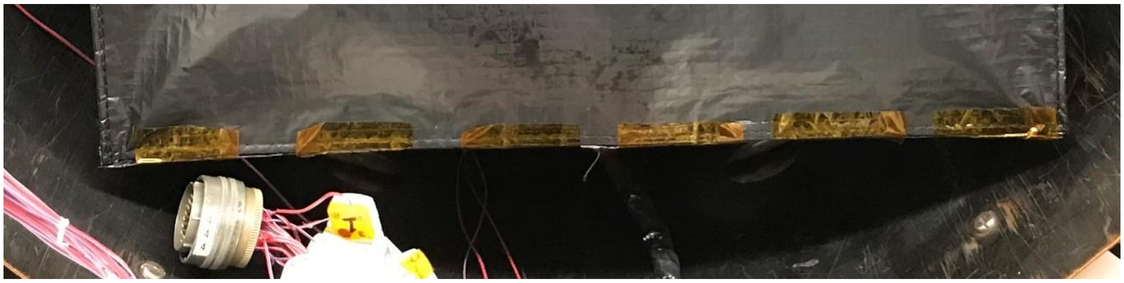

**Figure 11. Example of kapton tape closeout along bottom MLI panel.**

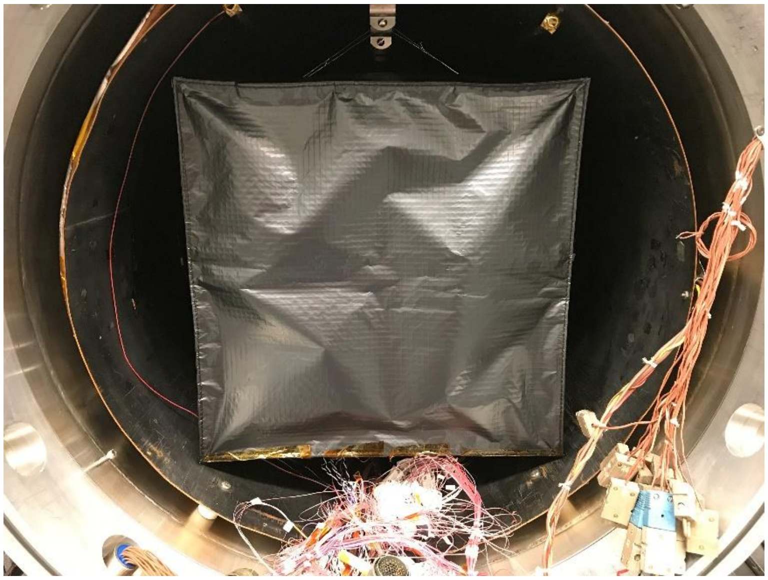

**Figure 12. The blanketed test article installed in the chamber. All thermocouple and heater wires egressed towards the front of the chamber.**

## IX. Baseline Blanket Testing

The baseline blanket design (Figure 12) consisted of 20 layers of aluminized Mylar with Dacron netting in between the layers. The inner and outer surfaces had a carbon filled black kapton coating. This type of blanket layup is consistent with a traditional JPL blanket design. The blanket was sized to 16 in x 16 in x 16 in (0.4 m x 0.4 m x 0.4 m) to accommodate 2 in (0.05 m) Mylar standoffs on all sides of the cube, which was 12 in x 12 in x 12 in (0.3 m x 0.3 m x 0.3 m).

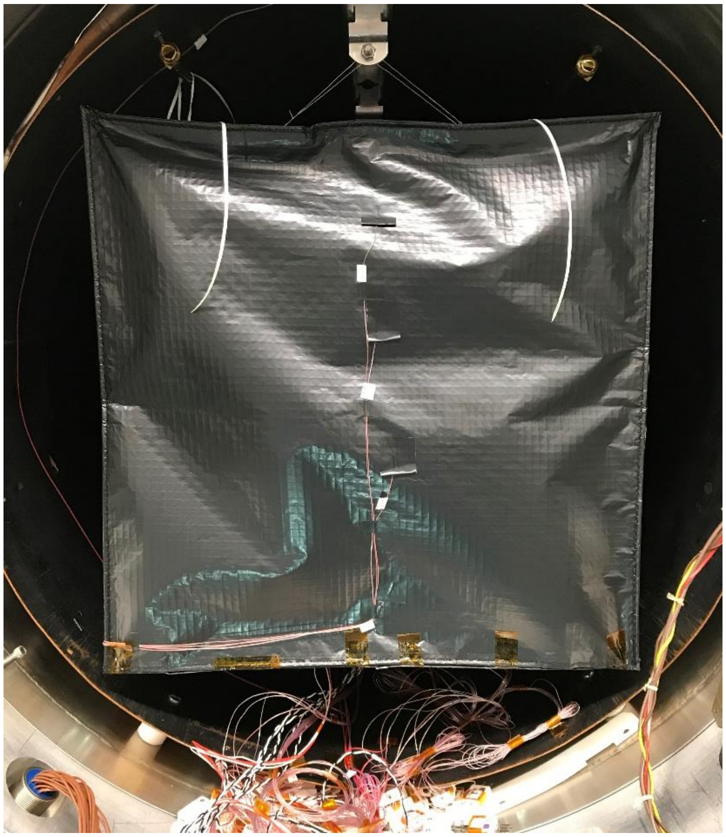

**Figure 13. The baseline 20 layer blanket in the chamber before testing. For this test, thermocouples were attached to the outermost layer of MLI and covered with black kapton tape.**

For the baseline blanket test, the outside of the MLI was instrumented with thermocouples. Since the outer layer of the MLI was black, it was expected that the temperatures on the outside of the MLI would be within several degrees of the chamber shroud, which was also black. During testing, there was around 10 °C difference between the four outermost side surfaces of the MLI and the shroud (Table 2). This confirmed pre-test intuition. However, the top and bottom surfaces had 20 and 50 °C differences respectively. The top surface of the MLI had slits cut into the blanket to accommodate the wire feedthroughs from the eyebolts. The bottom surface of the MLI had an extra seam to accommodate the cable bundle as well as a view to the cables, feedthroughs, and connectors resting on the bottom of the chamber shroud. Therefore, the larger temperature differences between MLI and shroud for the top and bottom surfaces were expected. These two sides of the blanket were excluded from the overall blanket performance calculations.

Thermocouples were not installed on the outside of the MLI for the remaining test cases. Since all blanket configurations had the same type of black outer surface, the temperature differences between shroud and outside of MLI should be consistent. Either way, the difference in $\varepsilon^*$ values calculated using the shroud temperatures instead of the outer layer MLI temperatures was negligible up to the ten-thousandths place. Removing and re-installing the thermocouples also would have added several hours of setup time for each blanket case. Any future test that requires more temperature fidelity may want to keep the MLI thermocouples, although the insensitivity of the results for this test shows such a decision is likely unnecessary. These outer MLI thermocouples would be needed in a future test if the outer surface coating were not a high emissivity surface.

| Location | North | East | South | West | Top | Bottom |
|---|---|---|---|---|---|---|
| Outer MLI | -164 | -165 | -163 | -167 | -152 | -126 |
| Shroud | -176 | -174 | -176 | -173 | -174 | -174 |
| ΔT | 13 | 9 | 13 | 7 | 22 | 48 |

**Table 2. Temperatures for the outer layer of MLI and shroud (°C) in the baseline blanket test. The MLI temperatures shown are the averages for each face of the cube.**

## X. Analytical Predictions and Test Results for All Blanket Cases

Before the test, analytical predictions of overall blanket emissivity, ε*, were made with the Lockheed equation. For a single blanket configuration, the blanket ε* can be calculated by simply using the equation. However, calculation for a dual blanket configuration is more complicated since calculating new ε* values will change the sink temperatures that each blanket sees. To overcome this, a numerical scheme was implemented in Microsoft Excel that iterates the ε* values of both blankets until the calculated temperatures result in an error smaller than some tolerance ($10^{-6}$).

There is another challenge with making analytical predictions that arises due to differences in blanket areas for dual blanket tests. In a single blanket test, there is only one blanket area, which makes an overall ε* calculation simple. However, for dual blanket test cases in which the blanket areas differ, it was important to use a blanket area consistent with the single blanket cases for calculating the overall ε* of the dual blanket system. As a result, the 16 in x 16 in x 16 in (0.4 m x 0.4 m x 0.4 m) outer blanket area (the larger of the two) was used as the reference so that all predictions were based on the same area. The simplified radiation heat transfer equation (referring to Fig 2), that provides the overall blanket emittance is as follows (assuming MLI ε* << 1 to simplify the terms in the equation):

$$\varepsilon_{large}{}^{*} = \frac{1}{\left(\frac{A_{large}}{A_{small}}\right)\left\{\frac{1}{\varepsilon_1^*}+\frac{1}{\varepsilon_{1,o}}\right\}+\left\{\frac{1}{\varepsilon_{2,i}}+\frac{1}{\varepsilon_2^*}\right\}} \tag{3}$$

where $\varepsilon_1^*$ and $\varepsilon_2^*$ are the effective emittances of the first and second blankets, respectively; and $\varepsilon_{1,o}$ and $\varepsilon_{2,i}$ are the emissivities of the exposed surfaces of the two blankets facing each other. $A_{large}$ is the area of the larger (outer) blanket and $A_{small}$ is for the inner blanket. The $\varepsilon_{large}$* value is defined from the test hardware (cube) to the outermost layer of MLI based on the outer blanket area. The predicted and as-tested ε* values for each test case are in Table 3.

| Case | Blanket Scheme | Inner ε* | Outer ε* | Predict Total ε* | Test Total ε* |
|---|---|---|---|---|---|
| 1 | 20 CK, DAM, CK | - | 0.0177 | 0.0177 | 0.0150 |
| 2 | 20 CK, DAM, CK (extra seams) | - | 0.0202 | 0.0202 | 0.0354 |
| 3 | 5 CK, EAK, CK + 2” + 15 CK, DAM, CK | 0.0466 | 0.0303 | 0.0137 | 0.0128 |
| 4 | 5 CK, EAK, AM + 2” + 15 AM, DAM, CK | 0.0497 | 0.0258 | 0.0070 | 0.0068 |
| 5 | 5 CK, DAM, AM + 2” + 15 AM, DAM, CK | 0.0497 | 0.0258 | 0.0070 | 0.0075 |
| 6 | 5 CK, EAK, AM + 2” + 15 AM, DAM, CK (staggered seams) | 0.0443 | 0.0244 | 0.0067 | 0.0072 |
| 7 | 2" + 5 CK, EAK, CK + 15 CK, DAM, CK (staggered seams) | 0.0425 | 0.0237 | 0.0091 | 0.0080 |
| 8 | 15 CK, EAK, AM + 2” + 15 AM, DAM, CK | 0.0190 | 0.0294 | 0.0051 | 0.0079 |
| 9 | 15 CK, EAK, AM + 2” + 15 AM, DAM, CK (staggered seams) | 0.0174 | 0.0282 | 0.0049 | 0.0086 |

**Table 3. Predicted and as-tested data for blanket performance, ε*. The ε* value was defined between the cube and the outermost layer of MLI. For a dual blanket case, “total” describes the overall combined ε*. Data is for test article at +35 °C.**

After testing, the ε* values were determined at each of the three different test article temperatures (+20, +35, +50 °C) for each test case. Since the top and bottom faces showed large temperature deviations compared with the four side faces (Table 1) due to artifacts of the test setup, only the results of the four side faces were included for determining overall blanket performance.

To calculate the ε* for one face of the blanket, the hot and cold sink temperature measurements and the outer blanket area were used with the Stefan-Boltzmann equation. The average of those four ε* values (one for each of the blanket's side faces) was calculated and represented the overall blanket ε*. The overall ε* values for each blanket case with the test article at +35 °C are reported in Table 3. The analytical predictions shown are based on a hot sink temperature of +35 °C, which is the midpoint of the three test temperatures. The values for +35 °C are shown since it was a representative average ε* for each blanket over the range of test article temperatures (+20 to +50 °C), although testing revealed there was little change to the ε* over this range.

The primary objective of this development test was to determine if any of the dual blanket concepts could reduce the heat loss from that of the 20-layer single blanket baseline. Table 4 shows the condensed version of the predicted and test actual ε* values for all test cases using the larger blanket areas. All of the dual blanket concepts (except case 3 which had carbon filled black kapton surfaces) had a roughly two times reduction in ε* from the baseline blanket design. Additionally, the use of Dacron netting vs. embossed aluminized kapton or normal vs. staggered seams made little impact on the blanket performance. The test cases that used two 15 layer blankets did not show improvement over a 5 and 15 layer blanket configuration.

| Case | Blanket Scheme | Total Predicted ε* | Total Test ε* | Test/ Predict | Case #/ Case 1 (Test) |
|---|---|---|---|---|---|
| 1 | 20 CK, DAM, CK | 0.0177 | 0.0150 | 0.85 | - |
| 2 | 20 CK, DAM, CK (extra seams) | 0.0202 | 0.0354 | 1.75 | 2.36 |
| 3 | 5 CK, EAK, CK + 2" + 15 CK, DAM, CK | 0.0137 | 0.0128 | 0.93 | 0.85 |
| 4 | 5 CK, EAK, AM + 2" + 15 AM, DAM, CK | 0.0070 | 0.0068 | 0.97 | 0.45 |
| 5 | 5 CK, DAM, AM + 2" + 15 AM, DAM, CK | 0.0070 | 0.0075 | 1.07 | 0.50 |
| 6 | 5 CK, EAK, AM + 2" + 15 AM, DAM, CK (staggered seams) | 0.0067 | 0.0072 | 1.07 | 0.48 |
| 7 | 2" + 5 CK, EAK, CK + 15 CK, DAM, CK (staggered seams) | 0.0091 | 0.0080 | 0.88 | 0.53 |
| 8 | 15 CK, EAK, AM + 2" + 15 AM, DAM, CK | 0.0051 | 0.0079 | 1.55 | 0.53 |
| 9 | 15 CK, EAK, AM + 2" + 15 AM, DAM, CK (staggered seams) | 0.0049 | 0.0086 | 1.76 | 0.57 |

**Table 4. Comparison between predicted and test values (using larger of two blanket areas where applicable). All data is for +35 °C.**

The test data showed good correlation to the predicts from the model, which demonstrated its efficacy for making realistic estimates of ε* for single and dual blanket designs. The three main exceptions for the good correlations were when two blankets of 15 layers each (Cases 8/9) were tested (30 layers total), or when the blankets had additional seams (Case 2) – in these instances the ε* predictions were significantly lower than those observed in the test. Since the extra seams were not accounted for in the prediction models, it is understandable that the test produced higher ε* values for obvious reasons explained before. However, the 30 total layers cases need further examination of the discrepancy in test vs. predictions. In the other cases, the ε* measured in test was slightly higher than the predictions. The analytical model was correlated to the test data by calculating the ratio of the as-tested ε* to the predicted ε*.

This creates a correction factor that can help adjust for artifacts of testing and any shortcomings of the Lockheed equation. Predictions for 0 °C, +35, and +50 °C using the correction factors were also performed (not included in this paper).

## XI. Power vs. Mass Trade

The driving motivation for this development test is to determine if there is an MLI concept that can save heater power required for the spacecraft. However, if power savings comes at the expense of a large mass increase (e.g. by adding layers), it may not be advantageous to pursue the improved MLI concept. To address the power versus mass trade study, the MLI performance was plotted against the total measured mass for each test case (Figure 14).

There are two main findings when considering this trade. The first is that all the dual blanket cases demonstrated an improvement in blanket performance over the single blanket baseline case. The second is that dual blanket performance was nearly independent of mass. Therefore, the optimal blanket design of those tested is the lightest of the dual blanket cases. For this reason, the recommended dual blanket design is the 5 layer embossed aluminized kapton blanket and 15 layer Dacron and aluminized Mylar blanket, both with aluminized "exposed" surfaces. The embossed aluminized kapton layup will be lighter since it does not need interstitial Dacron netting to separate the layers. Each project should consider its own thermal and mechanical requirements when choosing an MLI blanket layup design.

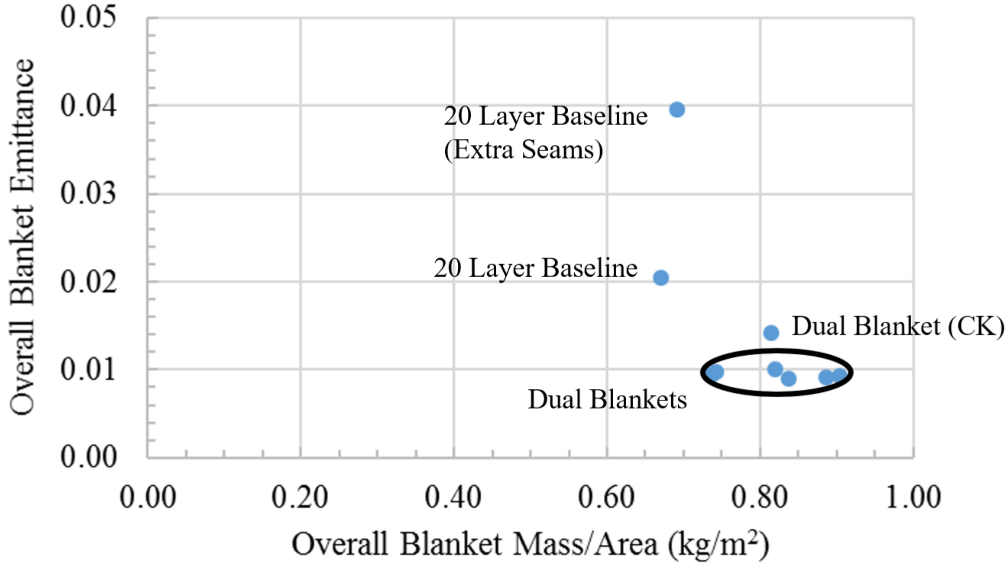


**Figure 14. Blanket performance as a function of the mass per area. The mass data was measured post-test.**

## XII. Lessons Learned for Testing

During and after testing, there were several lessons learned that are hopefully useful for improving future MLI tests:

1. Cooling below ambient temperature is very time consuming with an MLI wrapped test article. The time constant for these blankets was estimated to be about 50 hours to transition from +20 to 0 °C. Therefore, data was instead collected at temperatures between +20 to +50 °C. To collect data below ambient temperatures would have required a significant increase in test time and staffing, so it was not pursued at this time.
2. Fit checks should be anticipated before testing with the size of the MLI in mind rather than the size of the structural components. In this test, the test article with MLI was 16 in x 16 in x 16 in (0.4 m x 0.4 m x 0.4 m), which fits into the small chambers at ETL with less than a 1 cm on each corner.
3. All of the 36 AWG thermocouples functioned properly throughout testing. There was concern that a small wire gauge may be susceptible to damage during installation or from repeated thermal cycling over the course of many tests, however this was not the case.

4. Guard heating of the power and instrumentation cables should be done correctly to minimize parasitic heat losses from the test article, which would be a more accurate measurement of heat loss via MLI: the guard heater on the cables should be set to control to a temperature equal to that of the test article. This would avoid subtracting a calculated heat loss from these cables in the test to estimate the net loss from the test article via the MLI.

## XIII. Future Work

Since there are several blanket designs that outperformed the baseline blanket design, future testing at a larger scale should be conducted to validate these results in a more realistic implementation. This test would be at full-scale, contain a more flight-like representation of the propulsion module cylinder, feedthroughs & protrusions, and be more narrow in scope. This will better quantify how sewn seams influences blanket performance.

It is recommended that additional testing be done with the 20 layer CK, DAM, CK (case 1) and 5 layer CK, EAK, AM + 15 layer AM, DAM, CK designs (case 4). The latter is the optimal blanket with regard to maximum thermal performance and minimal mass. Future testing will validate the results of this test and determine a realistic range of $\varepsilon^*$ values. This will assist with thermal modeling and mission ops. This data would also be useful to other future missions that use MLI.

Although the innermost and outermost surfaces of all blankets were carbon filled black kapton, there is nothing that precludes the use of a low emissivity surface, such as an aluminized Mylar, for the flight blankets. Therefore, the blanket performance can be slightly improved beyond that seen in this test.

## XIV. Conclusions

This development test has shown that dual blanket concepts are viable for reducing heat loss from that of a single blanket on a small-scale. Most dual blanket cases resulted in roughly half the heat loss of a standard 20-layer blanket. Changes in the blanket layup (Dacron vs. embossed) and seams (normal arrangement vs. staggered) made little impact on the results in this test. Full-scale test using thermal pathfinder models of the actual flight hardware would validate the blanket's performance. That test can validate the findings of this test and determine more realistic values for blanket performance in a more flight-like configuration that includes feedthroughs and realistic geometry.

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